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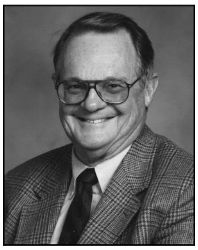
Remote Sensing of Particulate Pollution from Space: Have We Reached the Promised Land?



George Hidy

From the industrial revolution and before, airborne particles have been identified as a visible, perceptual marker of air pollution.[1] A long history exists of observations of the optical effects of fine particles in the atmosphere, beginning in the 11th century with a theory of Alhazen of Basra for sunlight scattering[2,3] and later perhaps Leonardo DaVinci in his recognition that the atmosphere was turbid and not clear. Combining the classical theories of Rayleigh and Mie for light scattering,[4] observations of atmospheric optical properties associated with suspended particles began in the 19th century. By the mid-20th century, knowledge of visibility and the role of particles in the earth's radiation balance expanded dramatically.[5,6] Remote sensing of the optical properties of the atmosphere from the ground expanded in the 1950s with global observations of sun photometry. Modern remote sensing of the sky in relation to aerosols at different heights was promoted through the introduction of ground-based light detection and ranging (lidar) in the 1960s.[7] About the same time, designs for passive instrumentation for aircraft and satellite applications began to emerge, and the development of the first wave of space-borne sensors accelerated with planetary exploration and interest in observing the earth from space.

In the 1970s, interest in the remote sensing for pollutant gas and particle concentrations began to appear in the Association's *Journal*[8] and other literature. Early observations with ground-based lidar in conjunction with conventional air pollution measurements took place beginning in 1972 and later in 1981.[9,10] Later, some of the first observations from satellites of regional- or synoptic-scale particulate pollution over eastern North America appeared in conjunction with ground- and aircraft-based observations in the 1977–1978 Sulfate Regional Experiment (SURE).[11,12] Since the 1970s, the remote sensing of particles in the atmosphere has increased dramatically from satellites, aircraft, and ground-based instrumentation. These observations have assisted in building knowledge of large to hemispheric scale conditions of ozone (O_3), nitrogen dioxide (NO_2), and haze and their origins in the troposphere and the stratosphere.[13,14] This work also led to the optimism that satellite sensing could offer an alternative to ground-based monitoring for tracking the long-term nature of pollution across the continents.

The 39th annual A&WMA critical review[15] examines the assertion that space-based remote sensing can now provide a major complement to ground-based monitoring for particulate pollution. The review begins with a brief summary of the fundamentals of space-based remote sensing for gases and particles noting Beer's Law as a starting point, and defining optical depth—aerosol optical depth (AOD)—as major measurable for satellite sensing. The review continues with a summary of the large number of satellites in orbit and their instrumentation in a passive and active mode. Examples are given of (a) observations of column burdens to elucidate air chemistry, (b) particle column burdens and how they are translated into estimated concentrations at or near ground level, (c) the use of space-borne observations to complement fixed monitoring networks with data between stations, and (d) the application of satellite data to characterize air pollution and identify sources and large-scale transport events.

The measurement of optical properties of fine particles, including extinction, scattering, and absorption in the UV, visible, and IR spectral range provide a means of inferring atmospheric particle burden. With the aid of lidar observations, aerosol concentrations with height can be estimated, including the boundary layer above ground. Under clear sky conditions and a well-mixed boundary layer, there is evidence that, on the average, estimates of fine particulate matter ($PM_{2.5}$) burdens are correlated well with ground-level observations, provided the humidity is taken into account.

The review notes the large number of earth-observing satellites that have been launched since the Television IR Observational Satellite (TIROS-1) weather monitoring platform launched into near circular, low-Earth orbit in 1960. Later, satellites have carried a broad array of instrumentation to observe the Earth through a wide range of the electromagnetic radiation spectrum from a nadir to various viewing angles of orientation. The spectral absorption in the molecular rotational and vibrational bands of gases, combined with knowledge of the average distribution of pollutant gases in the atmosphere with height, has enabled workers to investigate column burdens and inferred boundary layer concentrations of trace gases, such as formaldehyde and glyoxal to more common pollutants, such as NO_2, O_3, sulfur dioxide (SO_2), and carbon monoxide (CO). The measurement of optical properties of fine particles, including scattering and absorption in the UV, visible, and IR spectral range, provide a means of inferring the atmospheric particle burden and haze layers by height. With the aid of lidar observations, aerosol concentrations with height can be estimated, including the boundary layer above ground.

To date, the space-based observations of aerosol column burdens have been very useful for tracking regional haze progression (including dust storms and pollution) across continents and the oceans, plumes from shipping, and large sources of industrial activity, or from wildfires. The use of satellite data from boundary layer burdens are precluded by the presence of clouds. The variability of the surface albedo on land or surface waters roughened by wind also presents an ambiguity in the interpretation of data. The use of geostationary platforms offers an opportunity for averaging observations in a similar manner to fixed stations, but the spatial resolution is coarse ($\geq$10 km^2) compared with that needed for estimating human exposure conditions. Polar orbiting satellites provide much broader geographical coverage, but spatial-temporal averaging the aerosol burden in space and time for comparison with fixed sites is problematic.

Using relationships between light extinction or scattering and particle mass concentration, the (vertically averaged) particle concentrations can be inferred. Some data have been interpreted (qualitatively) for major composition components such as soil dust and black carbon using polarized light scattering and relationships with the index of refraction. Relating light extinction to particle mass from space, of course, has the same ambiguities that light scattering as a measure of mass concentration has at the ground. Correlating mass concentrations with extinction (or scattering) results in values of the ratio of mass concentration-to-light scattering coefficient of approximately $1.8^{+1.8}_{-0.9}$ g/m^2, based on nephelometer comparisons with filter-based sampling.[5,16,17] The report ends on an "unsurprising" note that the interpretation of satellite observations for air quality requires not only these measurements, but ground truth and the capability to manipulate data using models of atmospheric chemistry and meteorology.

This review complements two other recent reviews[18,19] dealing with the same topic. The views of Hoff and Christopher are as optimistic as others about relating satellite observations to ground-level air quality. All of them agree that for satellite observations to share the "burden" of providing data supporting sometimes contentious issues of air quality regulation,[20] the governing laws will have to be modified to accept the remote sensing approach to monitoring. In the meantime, the primary regulatory option for remote sensing is the identification of natural events like wildfires or dust storms, which may obviate apparent exceedances of the particle standards.

As a key alternative to the support of air quality regulations, satellite observations of particles are important in themselves for characterizing large spatial-scale phenomena in the atmosphere. The use of these data offer major opportunities to characterize the vertical structure of particle concentrations in the troposphere. Further, they serve to provide (a) continuing surveillance of source regions (e.g., for NO_2),[21] (b) a characterization of large-scale pollution transport events,[22] (c) an estimation of natural sources such as biogenic species,[23] and (d) yield constraints for continental-scale climate aerosol-forcing models.[24] Perhaps equally important, in my opinion, are the opportunities to support the determination of trends projected from the U.S. regional haze rule over the next half-century, as well inferring the significance of aerosols in meteorology and the dynamics of the air-ocean system. Recent papers complement past work on visibility trends[25] adding value by measuring continental trends in visibility,[26] and the large-scale influence of aerosols on such parameters as surface temperature of the Atlantic Ocean.[27] With the wealth of knowledge created by long-term spaced-based remote sensing, combined with ground and aircraft observations, we may have reached the "promised land," but it does not necessarily look like the one envisaged by enthusiastic scientists so many years ago in the 1960s.

The authors of the 39th annual A&WMA critical review are Drs. Raymond Hoff and Sundar Christopher. They are widely known experts in the field of analysis and interpretation of remote sensing observations, especially airborne particles. Dr. Hoff received his Ph.D. degree from Simon Fraser University in British Columbia. He is the director of the Joint Center for Earth Systems Technology and the Goddard Earth Science and Technology Center at the University of Maryland, Baltimore County. As a physicist, he has been active in satellite observational research for nearly 25 yr and has published more than 150 papers describing his research in remote sensing relevant to atmospheric chemistry. Dr. Christopher is a professor of atmospheric sciences and associate director of the Earth System Science Center of the University of Alabama at Huntsville. After receiving his Ph.D. in atmospheric science from Colorado State University in 1995, he has devoted his efforts to the study of atmospheric chemistry and physics using satellite remote sensing. He has served on the U.S. Climate Change Science Panel and is on various science teams, including a panel for the Global Energy Cycle and Water Experiment.

A&WMA members and guests are invited to read, attend, and comment on the 39th annual critical review at A&WMA's 102nd Annual Conference & Exhibition to be held in the Detroit the week of June 15. The presentation of the review and the discussants commentary is planned for Wednesday morning June 17, 8:00–11:30 a.m. EDT. The invited discussants include Dr. John Watson, research professor at the Desert Research Institute (DRI) (Reno, NV), Dr. Richard Scheffe (Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC), Dr. Aaron Samson (Northrop Grumman Aerospace Systems, Redondo Beach, CA), and Dr. Ernest Hilsenrath (NASA).

The discussants will provide different perspectives of space-based remote sensing, and will agree (or disagree) with the narrative and conclusions of the reviewers and of one another. They will identify additional issues and offer alternative commentary. Comments also will be solicited from the floor and from written submissions to the Critical Review Committee Chair. The Chair will condense and summarize these points in the October issue of the *Journal*. Members are encouraged to suggest topics and authors for future critical reviews and apply for membership on the Critical Review Committee to participate actively in the process.

George Hidy, *Critical Review Committee*

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